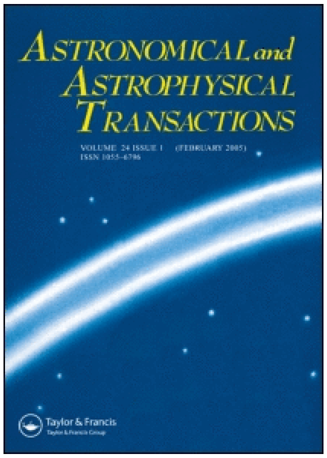

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 August 2007
To cite this Article: Shchekinov, YU. A. (2007) 'Charging of dust particles in molecular clouds', Astronomical & Astrophysical Transactions, 26:4, 227 - 234
To link to this article: DOI: 10.1080/10556790601156667
URL: http://dx.doi.org/10.1080/10556790601156667

Astronomical and Astrophysical Transactions
Vol. 26, Nos. 4–5, August–October 2007, 227–234

Taylor & Francis
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Charging of dust particles in molecular clouds

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(Received 21 August 2006)

In molecular clouds the dust charge can be determined by non-thermal electrons from cosmic-ray ionization. If the energy of the non-thermal electrons is $E \geq 2\,\mathrm{keV}$ and their fraction is only 10^{-3}–10^{-4} of the thermal electrons in a molecular gas, the grain charge can be as high as $|z| \approx 10$ in the range of gas densities $n \approx 10^5$–$10^6\,\mathrm{cm}^{-3}$. In the high-density range $n > 10^6\,\mathrm{cm}^{-3}$, the grain charge approaches the thermal limit $|z| \approx 0.3$.

Keywords: Interstellar medium; Molecular clouds; Dust; Charging; Non-thermal electrons

1. Introduction

Charged dust particles play a crucial role in the dynamics of molecular clouds. They determine, in particular, the structure of shock waves, the chemistry of shocked gas [1, 2] and the diffusion of the magnetic field in forming protostars [3]. In the conditions of molecular clouds the dominant process in the dust charging is the current from thermal electrons and ions, so that in equilibrium the charge obeys the equation [4]

$$n_{\mathrm{e}} v_{\mathrm{t,e}}\, \mathrm{e}^{-U} = n_i v_{\mathrm{t},i} (1 + U), \tag{1}$$

where n_{e} and n_i are the electron and the ion densities respectively, $v_{\mathrm{t,e}}$ and $v_{\mathrm{t,i}}$ are their corresponding thermal velocities, $U = e|\phi_0|/kT$, $\phi_0 = ze/a$ is the grain electrostatic potential, and the electrons and the ions are assumed to be in thermal equilibrium, *i.e.* $T_i = T_{\mathrm{e}}$. This gives the dust charge $z \simeq -2akT/e^2$; for typical conditions in molecular clouds with $T \approx 20\,\mathrm{K}$, $z \approx -0.3$ for particles with $a = 0.1\,\mu\mathrm{m}$ [5–7]. Such a low charge is a direct consequence of the exponentially small amount of Maxwellian electrons with energy sufficient to penetrate the Coulomb grain potential. It can therefore be expected that a power-law distribution of electrons provides a higher dust charge. This possibility was mentioned first in [8]. In this paper we estimate the contribution of non-thermal electrons that can be produced by the cosmic-ray (CR) ionization of a molecular gas to dust charging.

In section 2 we estimate the fraction of non-thermal electrons in molecular clouds arising from the ionization of molecular hydrogen by CRs. Section 3 contains the calculation of the

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Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790601156667

dust charge by non-thermal electrons with particular application to the conditions in molecular clouds. A summary is given in section 4.

2. Non-thermal electrons in molecular clouds

Non-thermal electrons are injected by the CR ionization with the rate

$$R(E) = \zeta n f(E), \tag{2}$$

where ζ is the primary ionization rate by CRs, n is the gas density and $f(E)$ is a function determined by the spectrum of the ionizing CR protons. In a uniform cloud with a homogeneous gas distribution the effects of spatial diffusion can be omitted. Then the density of the electrons is governed by the equation [9]

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}[b(E)N] + R(E), \tag{3}$$

where

$$b(E) = -\frac{\mathrm{d}E}{\mathrm{d}t} = -1.2 \times 10^{-20} n \left[3 \ln\left(\frac{E}{mc^2}\right) + 18.8\right] \mathrm{erg\ s^{-1}}, \tag{4}$$

is the ionization energy loss rate. In the stationary state the solution is

$$N(E) = |b(E)|^{-1} \int_E^{\infty} R(E')\,\mathrm{d}E', \tag{5}$$

with $R(E') = 0$ when $E' > E_M = 4\,m\varepsilon/M$, m is the electron mass, M is the proton mass and ε is the energy of the ionizing CR proton.

For CR protons with the spectrum

$$F(\varepsilon) = K\varepsilon^{-q}, \quad \varepsilon \geq \varepsilon_1, \tag{6}$$

the injection rate is

$$R(E) = \int_{\varepsilon_1}^{\infty} F(\varepsilon)\sigma(\varepsilon, E)\Theta(E_M - E)\,\mathrm{d}\varepsilon, \tag{7}$$

where $\sigma(\varepsilon, E)$ is the cross-section for a CR proton with energy ε to produce an electron with energy E and where $\Theta(E_M - E)$ is the Heaviside function. With the cross-section [10]

$$\mathrm{d}\sigma(\varepsilon, E) = \frac{\pi e^4}{\varepsilon}\frac{\mathrm{d}E}{E^2}, \tag{8}$$

this gives

$$R(E) = \frac{K\pi e^4 \varepsilon_1^{-q}}{qE^2}, \quad \text{for } E < \frac{4\,m}{M}\varepsilon_1, \tag{9}$$

and

$$R(E) = \frac{K\pi e^4}{qE^2}\left(\frac{4\,m}{M}E\right)^{-q}, \quad \text{for } E > \frac{4\,m}{M}\varepsilon_1. \tag{10}$$

We concentrate further on the high-energy electrons (equation (10)), because for the CR protons with $\varepsilon_1 = 1\,\mathrm{MeV}$ the upper-energy bound for δ electrons is only $4\,m\varepsilon_1/M = 2\,\mathrm{keV}$, and they thermalize on background electrons quickly – more rapidly than ζ^{-1}.

The primary ionization rate corresponding to the spectrum (6) is

$$\zeta = 2^{1/2} \frac{K\pi\hbar^2}{mq} \varepsilon_1^{-q}, \tag{11}$$

where the total ionization cross-section $\sigma(\varepsilon) = 2^{1/2}\pi\hbar^2/m\varepsilon$ [10] was used. Therefore, the injection rate (10) can be written in terms of ζ as

$$R(E) = \frac{me^4}{2^{1/2}\hbar^2} \left(\frac{M}{4m}\right)^q \frac{\varepsilon_1^q}{(1+q)} \frac{E^{-2-q}}{|b(E)|} \zeta. \tag{12}$$

Let us now calculate the total number of non-thermal electrons. In molecular clouds, low-energy CRs ($\varepsilon = 1$–$100\,\mathrm{MeV}$) seem to play a dominant role as the ionization source [11]. In this energy range the spectrum of CR protons is flatter than in the range $E > 1\,\mathrm{GeV}$. For conservative estimates, it can be assumed that $q = 1.5$, which gives, after integration of equation (12) over $E > 2\,\mathrm{keV}$,

$$N_\mathrm{e} = 2 \times 10^{12} \zeta. \tag{13}$$

It is readily seen from this that the number of non-thermal electrons can be quite comparable with the number of thermal electrons for a standard value of the primary ionization rate $\zeta = 10^{-17}\,\mathrm{s}^{-1}$. For instance, in dense molecular cloud cores with $n \approx 10^6 \mathrm{cm}^{-3}$ the abundance of thermal electrons is $n_\mathrm{e} = 16(\zeta\delta)^{1/3} n^{2/3}$ [12], and therefore the ratio

$$\beta = \frac{N_\mathrm{e}}{n_\mathrm{e}} = 2\delta^{-1/3} \zeta_{16}^{2/3} n^{-2/3}, \tag{14}$$

where δ is the depletion factor of metals on dust particles and $\zeta_{16} = \zeta/10^{-16}$. For the typical values $\delta \approx 0.1$, $\zeta_{16} = 0.1$ and $n \approx 10^6\,\mathrm{cm}^{-3}$, this gives $\beta \approx 10^{-4}$.

3. Contribution of non-thermal electrons in dust charge

In the orbital-motion-limited theory [13] the collection cross-sections for electrons and ions are written as

$$\sigma_\mathrm{e} = \pi a^2 \left(1 - \frac{2e|\phi_0|}{mv_\mathrm{e}^2}\right) \tag{15}$$

and

$$\sigma_i = \pi a^2 \left(1 + \frac{2e|\phi_0|}{Mv_i^2}\right), \tag{16}$$

respectively, where $\phi_0 = -ze/a$ is the potential at the grain surface, and the grain charge is explicitly assumed to be negative, such that $z > 0$. Assuming that the ambient plasma contains thermal ions with the fraction $1 - \beta$ of thermal electrons with equal temperatures $T_i = T_\mathrm{e} = T$, and the fraction β of non-thermal electrons with the spectrum

$$\mathrm{d}N(E) = \kappa E^{-\alpha}\,\mathrm{d}E, \text{ for } E_1 < E < E_2, \tag{17}$$

we can obtain using a standard procedure the following equation for the grain charge:

$$2\pi^{3/2} s_\mathrm{n} \left(\frac{kT}{E_1}\right)^{1/2} \left(\frac{\alpha - 1}{\alpha - \frac{3}{2}} \frac{E_1}{kT} - \frac{\alpha - 1}{\alpha - \frac{1}{2}} U\right) \beta + s_\mathrm{t} v_{\mathrm{t,e}} (1 - \beta)\,\mathrm{e}^{-U} = s_\mathrm{t} v_{\mathrm{t,i}} (1 + U), \tag{18}$$

for $\alpha > \frac{3}{2}$ and $E_2 \gg E_1$, where s_n and s_t are the sticking coefficients for non-thermal and thermal electrons respectively; from equation (12), $\alpha = 1 + q$. The deviation of the solution of equation (18) from the standard case of thermal collisional charging is determined by two parameters: E_1/kT and β. In molecular clouds with the temperature $T \approx 30$ K the first parameter can reach, as seen from section 2, $E_1/kT \approx 10^5$–10^6. Therefore, even for such a small fraction of non-thermal electrons as $\beta \approx 10^{-4}$ estimated above, the dimensionless potential U (and the grain charge) can be an order of magnitude higher than the thermal value; an order-of-magnitude estimate gives for these conditions $U \approx 30$ for $\alpha = 2.5$.

3.1 *Sticking coefficient*

When the charging of dust is determined by thermal particles, the sticking coefficient s is calculated as the average over the Maxwellian distribution of impinging particles [14]. For non-thermal electrons we evaluate s as

$$s = 1 - 2^{-x/T(E_0)}, \tag{19}$$

where x is the distance travelled by an electron with initial energy E_0 in the dust grain; $T(E_0)$ is the foil thickness required for 50% transmission of the electrons with initial energy E_0 (keV) [15] and is given by

$$T(E_0) \approx 300\rho^{-0.85} E_0^{3/2}\ \text{Å}; \tag{20}$$

here ρ (g cm^{-3}) is the grain density. We average s over the electron spectrum (17) with $E_1 = 2$ keV and $E_2 = 10$, 20 and 100 keV (figure 1), assuming, following [14], that the grain has an effective thickness $4a/3$. In comparison with charging by thermal electrons with $T \leq 10^5$ K where $\langle s\rangle \approx 1$ weakly varying with the grain size [14], non-thermal electrons with energies $E \gtrsim 10$ keV are stuck on dust grains less efficiently for smaller grains; for grains with $a \approx 100$ nm, the sticking coefficient is $\langle s\rangle \approx 0.6$ while, for $a \approx 10$ nm, $\langle s\rangle \approx 0.2$. A direct consequence of this is the fact that in this case the dust charge is not a simple linear function of the grain size.

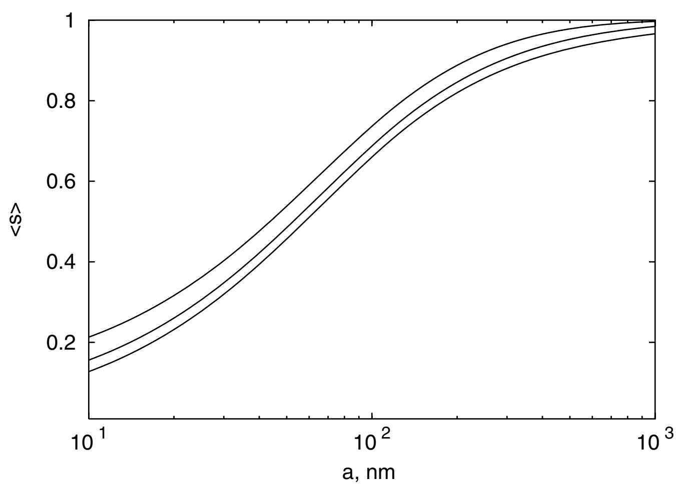

Figure 1. Sticking coefficient averaged over the spectrum of non-thermal electrons with $\alpha = 2.5$, $E_1 = 2$ keV and $E_2 = 10$, 20 and 100 keV from the uppermost to the lowermost curves respectively.

3.2 *Dust charge*

In figure 2 the solution U of equation (18) is depicted as a function of the gas density n for a set of E_1/kT values; the solid curves show $U(n)$ for $a = 100$ nm (0.1 μm), and the dashed curves $U(n)$ for $a = 10$ nm (0.01 μm). In the example shown here, $\delta = 0.1$, $\zeta_{16} = 0.5$; however, the results scale as $n\delta^{1/2}/\zeta$. In the limit of high densities ($n \gtrsim 10^7\,\mathrm{cm}^{-3}$) the grain potential U approaches its thermal collisional value of approximately 2.8 because higher densities reduce the ratio of the non-thermal to thermal electrons: $\beta = N_e/n_e$. However, in the range of low densities ($n \approx 10^3\,\mathrm{cm}^{-3}$) the potential U can reach about 10^2–10^3 depending on the ratio of the typical energy of the non-thermal electrons to that of the thermal electrons, E_1/kT. For molecular clouds with $T \approx 30$ K and the lower energy limit of non-thermal electrons $E_1 \approx 2$ keV, this ratio is approximately 10^6; in figure 2 this value corresponds to the upper curves, while the lower curves show decreasing values of E_1/kT, from 10^5 to 10^3 respectively. The grain charge is $z = 0.18a_{0.1}T_{30}U$, where $a_{0.1} = a/0.1$ μm and $T_{30} = T/30$ K; therefore, in molecular clouds with densities $n \leq 10^6\,\mathrm{cm}^{-3}$ and for $E_1 \geq 2$ keV, a typical grain charge can be met in order to reach $z \geq 10a_{0.1}^{2/3}$.

The grain potential is approximated as $U = 6 \times 10^5 E_1 a_{0.1}^{0.4}(\zeta_{16}/n)^{2/3}$ in the low-density (or high-potential) range $n < 2 \times 10^8 a_{0.1}\zeta_{16}E_1\,\mathrm{cm}^{-3}$ (or $U > 3$), where E_1 is in kiloelectronvolts. At high densities $n > 10^6 E_1^{-3}\zeta_{16}$, the charge zn_d accumulated on dust grains can become a substantial fraction of the charge carried by the non-thermal electrons. In other words, the charge contained in non-thermal electrons becomes exhausted and their efficiency to charge dust grains decreases; this effect is seen in figure 2 as a small increase in the slope of $U(n)$ curves for $E_1/kT = 10^5$–10^6 at densities n around $10^7\,\mathrm{cm}^{-3}$. However, in the intermediate-density range, $n < 10^7\,\mathrm{cm}^{-3}$, the decrease in the grain potential (and in the charge) is not significant, which means that the grain charge zn_d always remains considerably smaller than N_e. On the other hand, it follows from this that the electrostatic energy of the charged dust is always negligible in comparison with the electrostatic energy of the thermal electrons and ions: $zn_d/n_e \ll 1$.

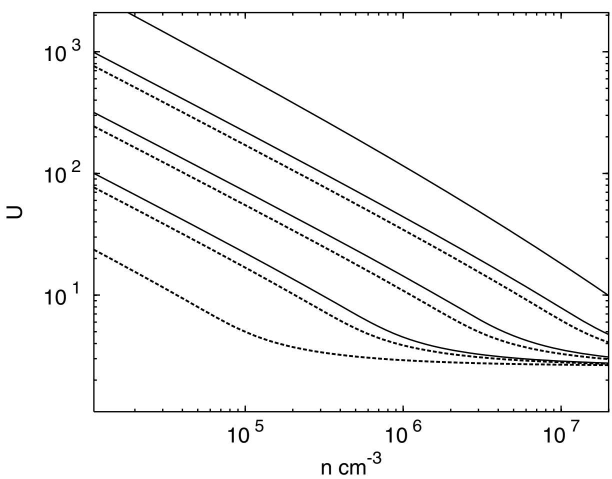

Figure 2. Grain potential U versus the gas density with a contribution from power-law non-thermal electrons with $\alpha = 2.5$, as argued in section 2, $\delta = 0.1$ and $\zeta = 5 \times 10^{-17}\,\mathrm{s}^{-1}$; the curves from the lowermost to the uppermost correspond to the low-energy cut-off values in the spectrum of non-thermal electrons of $E_1/kT = 10^3$, 10^4, 10^5 and 10^6 respectively. In the molecular gas with $T = 30$ K the top line corresponds to the minimum energy of non-thermal electrons $E_1 = 2$ keV. The solid curves show the potential U for grains with $a = 100$ nm (0.1 μm), and the dashed curves correspond to grains with $a = 10$ nm (0.01 μm). Note that the dimensional electrostatic potential ϕ_0 is negative in this case.

3.3 *Secondary-electron emission*

Each non-thermal electron in the energy range of interest $E > 2\,\mathrm{keV}$ impinging on a grain can produce emission of electrons from the bulk material of the grain: secondary-electron emission. The secondary-electron emission yield $y(E)$ for a spherical dust particle can be approximated as [14]

$$y(E) = 2\left[1 - \exp\left(-\frac{4a}{3\lambda_g}\right)\right] f_1\left(\frac{4a}{3T}\right) f_2\left(\frac{a}{\lambda_g}\right) y_\infty(E), \tag{21}$$

where λ_g is the escape length for a secondary electron, *i.e.* $e^{-l/\lambda_g}\,dl$ is the escape probability for a secondary electron created at a distance l from the surface, $f_1(x) = (1.6 + 1.4x^2 + 0.54x^4)/(1 + 0.54x^4)$, $f_2(x) = (1 + 2x^2 + x^4)/(1 + x^4)$ and

$$y_\infty(E) = y_m \frac{4E/E_m}{(1 + E/E_m)^2}; \tag{22}$$

the parameters y_m, E_m and λ_g of the secondary-electron emission (equation (21)) are given in table 5 of [14]. Figure 3 shows how the yield (21) depends on the energy of an impinging electron for graphite, SiO_2 and MgO grains. It is clearly seen from here that the secondary-electron emission can significantly diminish the efficiency of dust charging by non-thermal electrons, and in some cases, for instance for MgO grains, can reverse the sign. In figure 4 we show the dependence of the grain potential U on n for dust grains with $a = 100\,\mathrm{nm}$ and taking into account the effects from secondary electrons; the dimensional potential ϕ_0 is negative for graphite and positive for MgO grains in the whole range of n considered here, while SiO_2 grains have positive ϕ_0 at low densities ($n < 3 \times 10^6\,\mathrm{cm}^{-3}$) and negative ϕ_0 at higher densities. This behaviour can be easily explained from the characteristics of secondary-electron emission shown in figure 3: for graphite particles the secondary-electron emission yield is mostly less than one and therefore the grain charge remains negative everywhere (although lower by about 50–70% than when secondary-electron emission is neglected). For MgO particles, $y(E)$ significantly exceeds one in the energy range $E < 0.5\,\mathrm{MeV}$, so that the effects from secondary electrons completely cancel the effects from enhanced charging. The yield for SiO_2 grains has an intermediate magnitude and thus at high densities, when the

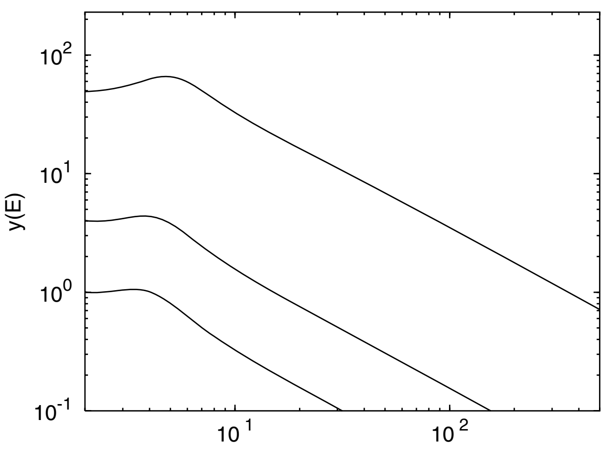

Figure 3. Secondary-electron emission yield $y(E)$ versus the energy of impinging electrons for graphite, SiO_2 and MgO, from the lowermost to the uppermost curves respectively; the grain radius $a = 100\,\mathrm{nm}$ ($0.1\,\mu\mathrm{m}$).

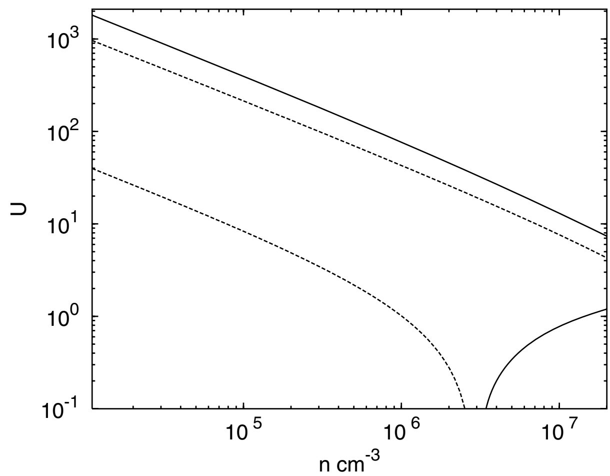

Figure 4. Grain potential U taking into account the secondary-electron emission for SiO_2, MgO and graphite grains from the lowermost to the uppermost curves. The solid curves correspond to negative dust charge, and the dashed curves to positive dust charge. The dimensional electrostatic potential ϕ_0 is negative for graphite in the whole density range and for SiO_2 at $n > 3 \times 10^6\,\mathrm{cm}^{-3}$, and positive for MgO particles in the whole density range shown here, and for SiO_2 at $n < 3 \times 10^6\,\mathrm{cm}^{-3}$; in all cases the low-energy cut-off in the spectrum of non-thermal electrons is $E_1 = 2\,\mathrm{keV}$, the gas temperature $T = 30\,\mathrm{K}$ and the grain radius $a = 100\,\mathrm{nm}$ (0.1 μm).

contribution from non-thermal electrons in charging becomes in general weak and thermal electrons dominate, it becomes negative. The charge of MgO grains also becomes negative only at densities $n \approx 10^8\,\mathrm{cm}^{-3}$.

4. Conclusions

(i) Ionization of gas by CRs in molecular clouds can produce a sufficient number of non-thermal electrons in the energy range $E > 2\,\mathrm{keV}$. The fraction of non-thermal electrons can be as high as 10^{-3}–10^{-4} depending on the gas density.

(ii) Non-thermal electrons can be more efficient in dust charging because of a slowly declining power-law energy spectrum. As a result, grains can have charges an order of magnitude higher than the thermal value $z \simeq 0.5 a_{0.1} T_{30}$.

(iii) Secondary-electron emission complicates the picture such that graphite particles remain negatively charged, MgO grains become positive, while SiO_2 grains are positive at lower densities and negative at higher densities. However, for graphite and MgO the absolute value of the dust charge remains considerably higher than that of the thermal electrons at $n < 10^7\,\mathrm{cm}^{-3}$.

Acknowledgements

This work was supported by the Federal Agency of Education (project code RNP 2.1.1.3483), by the Russian Foundation for Basic Research (project codes 05-02-17070 and 06-02-16819) and by the Deutsche Forschungsgemeinschaft within Sonderforschungsbereich 591 TP A6.

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